

Bounds and phase diagram of efficiency at maximum power for tight-coupling molecular motors

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The efficiency at maximum power (EMP) for tight-coupling molecular motors is investigated based on the constitutive relation between the flux and thermodynamic force. The motors are classified into four generic types (linear, superlinear, sublinear, and mixed types) according to the characteristic of the constitutive relation. Correspondingly, the EMP (η_*) for these four types of motors is proved to satisfy $\eta_* = 1/2$, $0 < \eta_* < 1/2$, $1/2 < \eta_* < 1$, or $0 < \eta_* < 1$, respectively. For the given reduced chemical potential $\Delta\mu$ which is the ratio of the released free energy of fuel in each motor step to the energy scale of thermal motion at the physiological temperature, the lower and upper bounds of EMP are found to be $[1 - \mathcal{W}(e^{1-\Delta\mu})]/\Delta\mu$ and $[\mathcal{W}(e^{1+\Delta\mu}) - 1]/\Delta\mu$, respectively, where $\mathcal{W}(\cdot)$ represents the Lambert's W function. A phase diagram with phase boundary $\delta = 2/\Delta\mu - 1/(e^{\Delta\mu/2} - 1)$ is constructed, which shows how $\Delta\mu$ and the load distribution factor δ influence on the EMP: The value of EMP is smaller than $1/2$ when the parameter pair $(\Delta\mu, \delta)$ takes value in the region above the boundary while larger than $1/2$ below the boundary. This fact implies that the motors using ATP as fuel under the physiological condition can work at maximum power with higher efficiency if $\delta \lesssim 0.1$, which provides a thermodynamic interpretation to several experimental observations on kinesin and myosin motors.

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Introduction. Molecular motors are special proteins which take charge of the long-distance transport in living cells [1]. The energetics of motors has attracted much attention from physicists since 1990s [2–8]. It is highly convinced that the operations of molecular motors abide by some economic principles of energetic managements because the motors are products of the long-term evolution and natural selection.

One of the possible economic principles might be that molecular motors work at the region of maximum power. To clarify this principle, Schmiedl and Seifert [9] optimized the power of molecular motors based on a generic model and found that the efficiency at maximum power (EMP) for tight-coupling molecular motors is $1/2$ when the motors work in the linear non-equilibrium region where the released free energy of fuel in each motor step is very small. They also deduced that the EMP can be larger or smaller than $1/2$ when the motors operate in the region far from equilibrium [9]. These results have been well confirmed and developed by other model systems [10–15], which can be regarded as the counterparts of the EMP for heat engines investigated by many researchers [16–25].

Recently, Van den Broeck *et al.* [15] derived the upper and lower bounds of EMP for tight-coupling molecular motors, and found that these two bounds can be reached when the transition state is close to the reactant state or the product state, respectively. However they expressed the bounds of EMP as the functions of thermodynamic force which depends on both the released free energy of fuel in each motor step and the external load on the motors. Both of them are in fact not independent of each other when the motors work at maximum power. Can

we express the bounds as the explicit functions of the released free energy of fuel in each motor step? In addition, most of the above researches reveal that the EMP of tight-coupling molecular motors can be larger or smaller than $1/2$, which depends on the load distribution factor (i.e., the position of the transition state) and the released free energy per fuel molecule (for example the hydrolysis energy of ATP). How do these quantities influence on the EMP of molecular motors? In this work, we will address these problems by investigating the EMP for tight-coupling molecular motors. The motors are classified into four generic types (linear, superlinear, sublinear, and mixed types) according to the characteristic of the constitutive relation between the flux and thermodynamic force. We obtain the corresponding ranges of EMP for these four types of molecular motors and express the bounds of EMP as the explicit functions of the released free energy of fuel in each motor step. A phase diagram is constructed, which implies that the motors using ATP as fuel under the physiological condition can work at maximum power with higher efficiency for the small load distribution factor, which provides a thermodynamic interpretation to several experimental observations on kinesin and myosin motors.

Model and optimization. We consider a simple translational molecular motor with equivalent discrete sites X_n ($n = 0, \pm 1, \pm 2, \dots$) with distance l between the nearest neighbor sites proposed by Schmiedl and Seifert [9]. As schematically shown in Fig. 1, the motor will consume one fuel molecule and move against the external load f in each step. That is, the chemical step and the mechanical step are tightly coupled. This process can be regarded

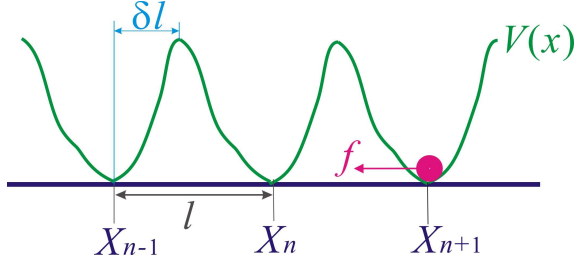
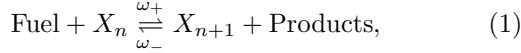


FIG. 1. (Color online) Scheme of the energy landscape $V(x)$. l and δ represent the step size and the position of transition state, respectively.

as a chemical reaction



where $\omega_+ = k_+ e^{-\delta fl}$ and $\omega_- = k_- e^{(1-\delta)fl}$ are the forward and backward rate constants, respectively. In the expressions of rate constants, we have not explicitly written out the energy scale ($k_B T$) of thermal motion at the physiological temperature. Thus fl in fact represents $fl/k_B T$ in the present work. k_+ (k_-) depends on the bare forward (backward) rate constant and the concentration of fuel (products). The load distribution factor $0 \leq \delta \leq 1$ indicates the position of the transition state, i.e., the distance between the transition state and the reactant state. The extreme cases $\delta = 0$ and 1 correspond to the situations that the external load merely influences on the backward or forward rate constants, respectively. Thermodynamic consistency [9] requires

$$\omega_+/\omega_- = e^{\Delta\mu - fl}, \quad (2)$$

where $\Delta\mu$ is called the reduced chemical potential which represents the ratio of the released free energy of per fuel molecule in the above reaction to the energy scale ($k_B T$) of thermal motion at the physiological temperature.

Let us consider the steady state where each sites have equal probability. The entropy production rate may be expressed as

$$\sigma = (\omega_+ - \omega_-) \ln(\omega_+/\omega_-) \quad (3)$$

with omitting a unimportant prefactor. The net flux is defined as

$$J = \omega_+ - \omega_-. \quad (4)$$

Thus the fundamental thermodynamic relation (*entropy production rate = flux \times thermodynamic force*) enlightens us that the conjugate thermodynamic force can be expressed as

$$F = \ln(\omega_+/\omega_-) = \Delta\mu - fl \quad (5)$$

with considering Eqs. (2)-(4). Then the constitutive relation between the flux and the thermodynamic force can

be expressed as

$$J = k_- e^{(1-\delta)\Delta\mu} [e^{\delta F} - e^{-(1-\delta)F}]. \quad (6)$$

The energy input per unit time for the tight-coupling motor can be expressed as $G = (k_B T \Delta\mu) J$. The power output is the difference between the energy input and the energy dissipation per unit time, which can be expressed as

$$P = G - k_B T \sigma = k_B T (\Delta\mu - F) J. \quad (7)$$

Thus the efficiency can be defined as

$$\eta = P/G = 1 - F/\Delta\mu. \quad (8)$$

It is stressed that we adopt the traditional definition of efficiency in the present work rather than the Stokes efficiency, rectification efficiency or sustainable efficiency proposed in recent Refs. [6–8, 22].

Our discussions so far can essentially be regarded as the concrete representations of the general considerations for the EMP of molecular motors in Refs. [10, 11, 15]. Now maximizing the power with respect to the external load f , we obtain

$$J/J' + F = \Delta\mu \quad (9)$$

from Eq. (7), where J' represents the derivative of the flux J with respect to the thermodynamic force F . Substituting the above equation into Eq. (8), we derive that the EMP satisfies the following relation

$$\eta_* = \frac{1}{1 + J'F/J}. \quad (10)$$

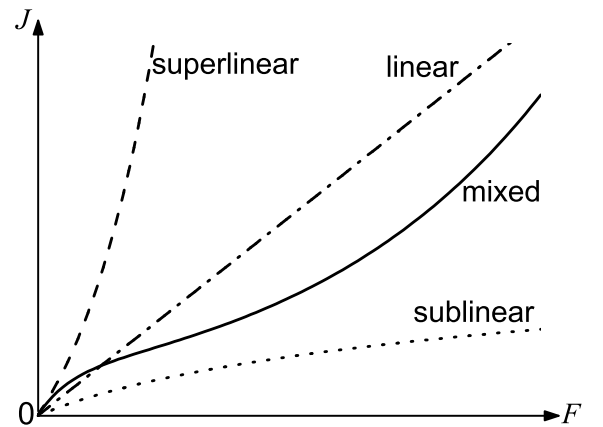


FIG. 2. Schematic diagram of four generic types of constitutive relations between the flux J and the thermodynamic force F .

Bounds of EMP. As we have done for heat engines in Ref. [26], we may classify motors into four generic types

according to the characteristic of constitutive relation between the flux J and the thermodynamic force F . As shown in Fig. 2, the motor is of linear type when the constitutive relation is linear, i.e., J increases uniformly with F . Similarly, a motor is of superlinear (sublinear) if the increasing rate of J is enlarged (reduced) with the increasing of F in the whole curve. Additionally, the motor is of mixed type if the increasing rate of J is enlarged with the increasing of F in some segment while reduced in the other one. In fact, the motor of this type crosses over from the sublinear type to the linear type and then to the superlinear type with the increasing of F , or vice versa.

The linear, superlinear and sublinear types of constitutive relation can be mathematically expressed as $J = J'F$, $J < J'F$, and $J > J'F$ for any finite F , respectively. Considering $0 < F < \Delta\mu$ and Eq. (10), we can easily derive

$$\begin{cases} \eta_* = 1/2, & \text{linear type;} \\ 0 < \eta_* < 1/2, & \text{superlinear type;} \\ 1/2 < \eta_* < 1, & \text{sublinear type.} \end{cases} \quad (11)$$

The constitutive relation of mixed type is a little complicated, which can be mathematically expressed $J > J'F$ in some segment (sublinear type) while $J < J'F$ in the other one (superlinear type), and $J = J'F$ at the demarcation point (linear type) between both segments. Correspondingly, the EMP can be larger or smaller than $1/2$, or equal to $1/2$ for the motor of mixed type, depending on which region F is located in. That is, the EMP for the motor of mixed type satisfies $0 < \eta_* < 1$.

Now we discuss three specific examples as follows. The first one is the situation that $\Delta\mu \ll 1$ so that $F \ll 1$. In this case, J is approximately a linear function of F . According to Eq. (11), we derive $\eta_* \rightarrow 1/2$ for $\Delta\mu \ll 1$, which confirms the previous result obtained in Refs. [9–15].

The second one is the limit case of $\delta = 1$. On the one hand, substituting $\delta = 1$ into Eq. (6), we derive the flux $J = k_-(e^F - 1)$ which displays the superlinear behavior ($J < J'F$) for any finite F . Thus Eq. (11) implies $0 < \eta_* < 1/2$. On the other hand, substituting the flux into Eq. (9), we can obtain the optimized $F_* = \Delta\mu - 1 + \mathcal{W}(e^{1-\Delta\mu})$ where $\mathcal{W}(\cdot)$ is the Lambert's W function [27, 28]. Substituting the optimized F_* into Eq. (8), we finally drive

$$\eta_1 \equiv \eta_*(\delta = 1) = \frac{1 - \mathcal{W}(e^{1-\Delta\mu})}{\Delta\mu}. \quad (12)$$

This analytic expression is plotted in Fig. 3, which reveals that the EMP indeed satisfies $0 < \eta_* < 1/2$.

The third one is the other limit case of $\delta = 0$. On the one hand, substituting $\delta = 0$ into Eq. (6), we derive the flux $J = k_-e^{\Delta\mu}(1 - e^{-F})$ which displays the sublinear behavior ($J > J'F$) for any finite F . Thus Eq. (11)

implies $1/2 < \eta_* < 1$. On the other hand, substituting the flux into Eq. (9), we can obtain the optimized $F_* = \Delta\mu + 1 - \mathcal{W}(e^{1+\Delta\mu})$. Substituting the optimized F_* into Eq. (8), we finally drive

$$\eta_0 \equiv \eta_*(\delta = 0) = \frac{\mathcal{W}(e^{1+\Delta\mu}) - 1}{\Delta\mu}. \quad (13)$$

This analytic expression is plotted in Fig. 3, which reveals that the EMP indeed satisfies $1/2 < \eta_* < 1$.

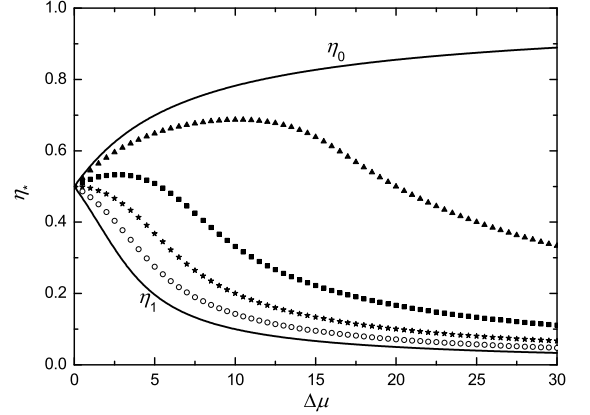


FIG. 3. Curves of EMP for tight-coupling molecular motors. η_1 and η_0 represent the EMP for $\delta = 1$ and 0 which can be analytically expressed as Eqs. (12) and (13), respectively. The triangles (▲), squares (■), stars (★) and circles (○) correspond to the EMP for $\delta = 0.1, 0.3, 0.5$ and 0.7 , respectively.

In general case, from Eq. (6) we can prove that the motor is of superlinear type ($J < J'F$) for $1/2 \leq \delta < 1$. Thus the EMP should be smaller than $1/2$ for $1/2 \leq \delta < 1$. On the other hand, it is not hard to find that the motor is of mixed type for $0 < \delta < 1/2$ through simple calculations from Eq. (6), and that the corresponding constitutive relation displays the behavior similar to the solid curve in Fig. 2. Then the EMP can be larger or smaller than $1/2$ for different values of $\Delta\mu$. A natural problem is to investigate the exact bounds of EMP for given value of $\Delta\mu$.

Substituting Eq. (6) into Eq. (9), we derive

$$\delta = \frac{1}{\Delta\mu - F} - \frac{1}{e^F - 1}. \quad (14)$$

We cannot solve the analytic solution to this equation if $\delta \neq 0$ or 1 . However, we readily see that δ is a monotonically increasing function of F for given $\Delta\mu$ because we find $\partial\delta/\partial F > 0$ from the above equation. Equivalently speaking, F is also the monotonically increasing function of δ for given $\Delta\mu$. Additionally, Eq. (8) implies that the efficiency is the monotonically decreasing function of F . Thus η_* should be the monotonically decreasing function of δ for given $\Delta\mu$. It follows that η_* is bounded by η_1 and η_0 , that is

$$\frac{1 - \mathcal{W}(e^{1-\Delta\mu})}{\Delta\mu} \leq \eta_* \leq \frac{\mathcal{W}(e^{1+\Delta\mu}) - 1}{\Delta\mu}, \quad (15)$$

which is the first main result in this work. We note that Van den Broeck *et al.* also derived the bounds of η_* in Ref. [15]. However they expressed the bounds as the functions of F which depends on both $\Delta\mu$ and f . Here we express the bounds as the explicit functions of single variable $\Delta\mu$.

We also find numerical solutions to Eq. (14) for $\delta = 0.1, 0.3, 0.5$ and 0.7 with various values of $\Delta\mu$. Then the numerical relations between η_* and $\Delta\mu$ are achieved from Eq. (8) and shown in Fig. 3 as triangles, squares, stars and circles for $\delta = 0.1, 0.3, 0.5$ and 0.7 , respectively. Obviously, all numerical data are indeed located in the region bounded by η_1 and η_0 , which is consistent with inequality (15). In addition, η_* is always smaller than $1/2$ for $\delta = 0.5$ and 0.7 while can be larger or smaller than $1/2$ for $\delta = 0.1$ and 0.3 . This fact is consistent with our above discussions because the constitutive relations corresponding to $\delta = 0.5$ and 0.7 are of superlinear type while those corresponding to $\delta = 0.1$ and 0.3 are of mixed type.

Phase diagram. There are two parameters in the present model: one is the load distribution factor δ ; another is the reduced chemical potential $\Delta\mu$. We will concern how these two parameters determine η_* to take value larger or smaller than $1/2$. Since we have proved $\eta_* = 1/2$ in the trivial case of $\Delta\mu = 0$, we only discuss the case of $\Delta\mu > 0$ in the following contents. To address this problem, we first find the condition (the relation between δ and $\Delta\mu$) to make $\eta_* = 1/2$. It follows that $J'F/J = 1$ and $F = \Delta\mu/2$ from Eqs. (9) and (10). Considering Eq. (6), we derive

$$\delta = \frac{2}{\Delta\mu} - \frac{1}{e^{\Delta\mu/2} - 1}. \quad (16)$$

That is, when δ and $\Delta\mu$ satisfy the above relation, η_* should always be $1/2$. Since we have proved that the efficiency is a monotonically decreasing function of δ for given $\Delta\mu$ in the above discussion, we can readily deduce $\eta_* > 1/2$ if $\delta < 2/\Delta\mu - 1/(e^{\Delta\mu/2} - 1)$ and vice versa. This is the second main result in the present work.

We draw the phase diagram in Fig. 4 according to the above analysis. The phase boundary is described by Eq. (16). When δ and $\Delta\mu$ take values in the region above the boundary, the motor can work at maximum power with lower efficiency ($< 1/2$). On the contrary, when δ and $\Delta\mu$ take values in the region below the boundary, the motor can work at maximum power with higher efficiency ($> 1/2$). In Table I, we list the numerical results of η_* for several values of δ and $\Delta\mu$ and the positions of the pair $(\Delta\mu, \delta)$ in the phase diagram. These numerical results indeed support our above predictions from the phase diagram.

In Ref. [9], Schmiedl and Seifert argued that the long-term evolution and natural selection might shape the ability that motors can work at maximum power with higher efficiency. Their insight can be easily understood

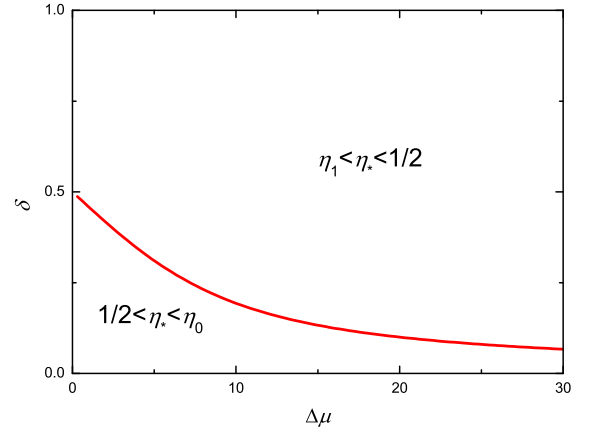


FIG. 4. (Color online) Phase diagram. The solid curve is the phase boundary described by Eq. (16) which separates the parameter plane into two regions. The value of EMP is smaller than $1/2$ when the parameter pair $(\Delta\mu, \delta)$ takes value in the region above the boundary while larger than $1/2$ below the boundary.

with the aid of the phase diagram according to which the parameter pair $(\Delta\mu, \delta)$ should be located in the region below the boundary. For the motors using ATP as fuel, $\Delta\mu \approx 20$ under the physiological condition, we calculate $\delta < 2/\Delta\mu - 1/(e^{\Delta\mu/2} - 1) \approx 0.1$ which is in good agreement with several experiments on kinesin and myosin motors where the small δ (< 0.1) was observed for the main motor step [29–32].

TABLE I. The numerical results of η_* for some values of δ and $\Delta\mu$.

$\Delta\mu$	δ	Position	η_*
5.0	0.311	On the boundary	0.50
10.0	0.193	On the boundary	0.50
20.0	0.100	On the boundary	0.50
5.0	0.7	Above the boundary	0.27($< 1/2$)
10.0	0.5	Above the boundary	0.20($< 1/2$)
15.0	0.2	Above the boundary	0.33($< 1/2$)
5.0	0.1	Below the boundary	0.65($> 1/2$)
15.0	0.05	Below the boundary	0.78($> 1/2$)
20.0	0.01	Below the boundary	0.85($> 1/2$)

Conclusion and discussion. In the above discussions, we investigate the EMP for tight-coupling motors. It is found that this efficiency is bounded by $\eta_1 \equiv [1 - \mathcal{W}(e^{1-\Delta\mu})]/\Delta\mu$ and $\eta_0 \equiv [\mathcal{W}(e^{1+\Delta\mu}) - 1]/\Delta\mu$ as shown in Fig. 3. We obtain a phase diagram (Fig. 4) of parameters δ and $\Delta\mu$ and determine the phase boundary by Eq. (16). Considering the argument that motors might operate at maximum power with higher efficiency [9], we derive $\delta \lesssim 0.1$ for the motors using ATP as fuel under the physiological condition, which provides a ther-

modynamic interpretation to several experimental observations on kinesin and myosin motors. Finally, we clarify several points as follows that have not been emphasized in the above discussions.

i) It is a little subtle to take $1/2$ rather than other values as the threshold to distinguish the higher efficiency from the lower one for motors when we construct the phase diagram. The most reasonable philosophy comes from the Darwinism. If the efficiency of some motors is smaller than $1/2$, then the energy dissipation is larger than the useful energy. That is, most of the input energy is wasted by the motors. This kind of motors might be unfavorable for the natural selection, therefore they will easily be extinct in the evolution. Combining this consideration, the phase diagram in this work, and the experimental data on kinesin and myosin motors, we propose to refine and develop Schmiedl and Seifert's argument into an economic principle of energetic managements: the long-term evolution and natural selection shape the good performance of molecular motors such that they can operate at maximum power with efficiency larger than $1/2$.

ii) The analysis in the present work might be extended to discuss the bounds of EMP for information machines or the Feynman ratchet investigated in recent literature [33–35]. At a glance, the EMP of the Feynman ratchet derived in our previous work [35] might in fact be the lower bound because it corresponds to the case of $\delta = 1$. However, in the recent work [36], Van den Broeck and Lindenberg found that the EMP for classical particle transport and the EMP of the Feynman ratchet share the same expression, which seems to imply that the EMP of the Feynman ratchet should be independent of δ . It is indeed not hard to verified this point based on the discussions in the present work.

iii) All discussions in the present work are merely focused on a minimal model with discrete sites where the internal states are neglected. While the main prediction $\delta \lesssim 0.1$ of this minimal model is in good agreement with most of experimental observations [29–32], a transition state in the range $\delta \simeq 0.3 - 0.65$ has also been extracted [37] based on a seven-state model. It is necessary to investigate how the model with internal states influences on the bounds and phase diagram in this work.

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